PRESSURE RELIEF - THE NEXT MAJOR CHALLENGE?©

F.P.Nichols
ICI Engineering, Brunner House, Northwich, Cheshire

SYNOPSIS

Process design methodology for emergency relief has developed over the last 10 years to provide 'safe' relief vents. Increasing environmental concern suggest that in the future the material vented may require treatment before discharge. The design basis for such a treatment system is explored. The accepted relief 'safe' flowrate is shown to be 'unsafe' for a treatment system. A possible 'safe' bound is developed, but there remains the major challenge of developing a secure methodology for the design of treatment systems.

Keywords: Pressure Relief, Emergency Vent, Relief Treatment, Design, Two-phase Flow.

INTRODUCTION

Emergency vents from process equipment are by definition, rarely expected to be required. The vent has often discharged directly to the atmosphere, and the (slight) risk of damage or injury has been deemed acceptable.

The design and sizing of such vent systems and their relief valves, bursting discs and associated pipework, has become less empirical and technically sounder with time, although the relatively less common and technically more demanding reactor vent designs remained largely empirical into the 1980's.

Pioneering vent models by Boyle in 1967 (2) and Huff in 1977 (3) began to introduce physical concepts to reactor venting, but major advances only began in the early 1980's under the Design Institute for Emergency Relief Systems - DIERS (4). This was a US based cooperative research programme sponsored by some 29 major Chemical Companies and ran from 1976 to 1984.

The users of DIERS methodology continue to meet regularly in US under the auspices of the AIChE and in Europe.

Consideration of treatment system design has only recently started (eg CCPS (12)), and the development of a design methodology for low cost and effective systems which are 'safe' is the next major challenge in pressure relief.

BASIS FOR RELIEF DESIGN

Pressure relief systems on process plant are designed so that the equipment design pressure is not exceeded. Methodologies for design are available - eg API 521 (1) or the DIERS Manual(4).

The relief design for runaway reactions requires first determining how much has to be relieved from a reactor to avoid overpressurization. This is essentially finding the peak rate at which volume is generated within the reactor by gas evolution or vapour generation/boiling. This is the required relief rate, and can be determined experimentally. (Ch 6 of ref 4)

Secondly calculating the size of the vent system to handle this rate. This is expressed as a (one or two phase) flow from the vessel and through the vent system driven by the vessel design pressure.

The DIERS approach to this calculation is based on two key assumptions - homogeneous venting from the vessel at the vessel design pressure and homogeneous flow down the vent line. These are well established as the worst case assumptions which lead to the largest vent diameter and hence a 'safe' vent design.

Any downstream catchment and disposal system would normally be designed on the basis of this flowrate and vessel pressure.

However the homogeneous venting and flow assumptions are pessimistic. The actual flowrate may be higher than design, *and/or the actual vessel pressure may be lower. In both cases the* relief system remains 'safe'. However the catchment system will then be subjected to a higher flowrate and/or lower inlet pressure, and is unlikely to achieve the required design performance. The design of the catchment system is therefore 'unsafe'.

The homogeneous assumption sets a lower bound flow 'safe' for the design of a relief system. A corresponding upper bound flow 'safe' for the design of a catchment system is required.

Note that the reaction runaway itself sets an additional bound to the required (volume) rate which is to be vented. This increases if the pressure during relief falls below the vessel design, but can be calculated for any given fall in relief pressure.

A TREND IN PRESSURE RELIEF DESIGN

There is greater awareness of the environment by the Public and within Industry and Government. This is leading to concern about possible effect of emissions to the atmosphere - including from emergency pressure relief vents. These concerns, combined with a wish to minimise loss of material, is leading the Chemical Industry to explore means of achieving safe operation without atmospheric venting of pressure relief systems.

Techniques available include:

1. Total containment/inherently safe designs
2. Avoiding the relief event by process control / instrumented trip systems
3. Reduction of inventory of chemicals in reaction or processing
4. Catchment, treatment and safe inert disposal of the relieved material
5. Quenching or inhibition of runaway reactions

Total containment/inherent safety within the process equipment or within a dump tank can often be achieved by increasing the volume and pressure rating of the equipment. Whilst many possible relief events can be contained, it can be technically difficult to contain liquid thermal expansion, runaway reaction or external fire without adopting other techniques as well. An increased pressure rating can also increase the potential hazard from vessel failure.

Process control can effectively prevent runaway reactions but requires high standards of design and operating reliability on the instrumentation. It can not replace relief for to external fire or liquid thermal expansion; a backup relief system is again required.

Reduced inventory clearly and desirably reduces the quantity of material relieved, but cannot solely eliminate relief.

Quenching or reaction inhibition can stop runaway reactions, but like process control, cannot entirely eliminate relief from external fire or liquid expansion.

A catchment, treatment and disposal system is ultimately the only technique which can handle all possible relief cases. Such a system can render the relieved material safe and inert before release to the environment.

RELIEF CATCHMENT AND TREATMENT SYSTEM

A relief catchment, treatment or disposal system will have to handle material that is often two phase boiling / flashing, at high temperature and pressure and possibly still reacting. It also has to be designed to handle high flow, short duration but very rare events at high reliability.

Clearly key design targets must be to kill any reaction, to cool/quench the material to reduce flash vapour, to separate vapour and liquid before any treatment and to make the process equipment passive or self-acting.

Techniques available include some or all of:

- dump tank or catchpot, possibly including a reaction killer/quench;
- quench pot to cool the material by direct contact with a large mass of inert liquid;
- gas/liquid separator or cyclone to separate the vapour and liquid;
- treatment of the remaining gas/vapour eg by absorbing in liquid reagents;
- incineration/flaring/thermal oxidation to handle flammable or toxic gases;
- treatment or recovery of the liquid material from the catchpot / quench or dump tanks / absorber.

Such a catchment system involves a number of process units and operations and may require a significant proportion of the total plant capital. There is a strong incentive to design the system to minimize equipment size and cost.

Design conditions for a treatment system

To specify such a system the expected maximum flowrate coming forward from the relief vents is required. This maximum flowrate should include a suitable design safety factor.

We do not know what the relief flowrate to the disposal / catchment system is, nor do we even have any established method for setting an upper bound. All we have, as discussed above, is a minimum flowrate based on the homogeneous vessel and homogeneous flow assumptions. This gives a 'safe' relief design, but an 'unsafe' catchment system design.

Let us consider the assumptions on which the relief design is based:

1. Homogeneous vessel venting - the 2 phase fluid vented from the reactor has the same composition (eg density, vapour fraction, etc) as the vessel contents averaged over the whole volume including any vapour space.

2. Homogeneous vent flow - the two phase vapour/liquid flow vented through the relief system is homogeneous - defined as liquid and vapour flows having the same velocity.
(It is unfortunate that the term 'homogeneous' has become established with two different meanings.)

3. Phase equilibrium is maintained - the flow is assumed to be adiabatic with the two phases everywhere at local thermodynamic, temperature and pressure equilibrium. This assumption enables a simple exact energy balance to be used and has been shown to be valid for flow path lengths above some 100mm. (Section 3-2-3-3 of ref 4)

There are three questions to ask of each:
1. How big an effect do these assumptions have on the actual flow?
2. Is there an upper bound we can place on the flow which is safe for the design of the catchment system?
3. Is it possible to make a better assessment of the true flow?

Homogeneous venting assumption.

For homogeneous venting we can set both an upper and lower bound - the material leaving the vessel must physically lie between all vapour and homogeneous 2-phase of the same density as the mean vessel contents. The known runaway reaction is independent of the venting behaviour, so all vent flows between these bound must have the same volume rate and can be readily calculated using zero-slip flow correlations for the vent piping (J C Leung (5,6)).

Typical variation of volume and mass flow rate with vapour volume fraction (or void fraction) is shown in fig 1 for flashing choked water/steam flow through an orifice. For a vent sized on the basis of homogeneous venting from a vessel 85% full (voidage 0.15), a single phase vapour flow will be 50x greater in volume or 1/5x smaller in mass than the homogeneous flow at the same driving pressure of 5 bara provided the reaction can generate such a flow.

This is interesting, but is not yet the flow through the catchpot system. The catchpot is likely to be near to ambient pressure, so that any liquid in the inlet flow will flash, giving a larger vapour flow and lower liquid flow from the catchpot. Detailed calculations shown in fig 3 for this water/steam system show that the greatest catchpot liquid load corresponds to reactor homogeneous venting, and the greatest catchpot vapour load corresponds to reactor vapour only venting. This is reduced by flashing from 50x to only some 2x homogeneous load on a volume basis. The critical design parameter for a catchpot is the vapour volume load, so this is the required upper bound at, typically, some 2x lower bound. It can be readily calculated.

The two bounds of homogeneous venting and vapour only flow correspond to none or complete vapour-liquid separation in the void space of the vessel. Partial separation is also possible and will give intermediate flowrates. However the incentive to evaluate this is small where the upper and lower bounds lie within a factor of 2.

Partial phase separation in the vessel can be estimated using the DIERS (4) correlations for a non-foaming system, but the reliability of the result is critically dependent on the nonfoaming assumption. Most systems, sadly, are foamers, and there is no method for estimating phase separation in a foamy reactor. Even for systems which are normally non-foamers, there remain grave doubts whether they will remain so during the unusual conditions of temperature, pressure and possible contamination which cause or occur during a reaction runaway. A few ppm of a surface active agent can turn a nonfoamer into a very nice foamer!

We propose that the 'safe' upper bounds for catchpot design should be the flashed liquid flowrate based on homogeneous reactor venting and the vapour flowrate based on vapour only reactor venting, provided the reaction can produce it.

Homogeneous vent flow assumption

We have a lower bound in the homogeneous vent flow assumption. No upper bound is known, although there is a physical limit of sonic vapour and zero liquid flow velocities.

Experimental data for two phase choked flow are compared with the homogeneous lower bound flow in fig 3 for non flashing air/water flows and in fig 4 for flashing steam/water flows (S.D. Morris 13). The experimental flows have been expressed as a multiple of the homogeneous flow.

The nonflashing flow is some 2 - 3 x homogeneous flow, peaking at a vapour mass fraction about 0.05, or a volume fraction about 0.98.

For flashing flow the experimental flow is over 10x homogeneous flow with no limit or bound apparent at lower vapour mass fractions. The scatter of data is also wide, with flow multiples ranging from 3x to 10x at vapour mass fractions about 0.01. Note that for a vapour void fraction about 15% for homogeneous venting from a 85% full reactor, we have a mass fraction about 0.0005 for 5bar steam/water, which, from fig 4, suggests an actual flow rate at least 15x homogeneous. This undersizing is significant, but can not be generalised to a general fluid system.

Although there is no upper bound, there are nevertheless several simple choked flow models for separated gas/liquid flow using the classic momentum and energy balances with the vapour / liquid velocity ratio as a free parameter (7,8,9,10,11). These, although developed for steam/water/air systems, can be generalized. These models variously use momentum, energy or entropy criteria to develope a maximum flow and each author show that his model agrees with his experimental data. The criteria used can all be approximated by equating the vapour / liquid velocity ratio to the 1/2 or 1/3 root of the liquid/vapour densities. There is no basis for choosing between these models, and as the 1/2 root yields a higher flowrate, it is therefore preferred as 'safer' rather than 'better'.

These models are, of course, based on separated flow and although they appear to fit experimental data, do not exclude the possibility that other flow models such as disperse flow may be as good or preferable.

Lacking any information, and with a catchpot to design tomorrow, the pragmatic solution would be to use the square root density ratio for the vapour / liquid velocity ratio to estimate the choked flow rate and take this as an upper bound for design. This recommendation accepts that the approach may be wrong and still 'unsafe', but it is not half as 'unsafe' as the homogeneous flow assumption.

CONCLUSIONS

We conclude that the upper and lower bounds to the vessel venting problem can be determined using existing methodology. However, for the vent flow problem we have no upper bound and no theory. Empirically the real flows can be much larger than the lower bound and some estimate of the upper bound is therefore required. Estimation using slip flow models is suggested as a pragmatic design basis where the vapour/liquid velocity ratio is equated to the square root liquid/vapour density ratio.

We suggest as current challenges in pressure relief:

- prediction of foam and carryover in reacting systems
- validation of the 2 phase flow models for the general case
- develop a methodology for the selection and design of vent treatment systems.

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REFERENCES

1. API RP521 "Guide for pressure relieving and depressurizing systems", American Petroleum Institute, Washington, 3 ed,1990

2. W J Boyle "Sizing relief area for polymerization reactors", 1967 Chem Eng Prog 63(8) 61

3. J E Huff "General approach to the sizing of emergency pressure relief systems", 2nd Int Symp Loss Prev in Process Industries, Heidelberg, Sept 1977

4. H G Fisher et al,"Emergency relief system design using DIERS technology", the DIERS Project Manual, AIChE, New York, 1992

5. J C Leung "Generalized correlation for one component homogeneous equilibrium flashing choked flow", 1986 AIChEJ 32 1743

6. J C Leung "Two phase flow discharge in nozzles and pipes", 1990 J Loss Prev Proc Ind 3 27

7. G B Wallis "One dimensional two phase flow" McGraw-Hill,New York,1969

8. S.M.Zivi, "Estimation of steady state steam void fraction by means of the principle of minimum entropy production", 1964(5) J Heat Tr 247-252

9. J E Cruver, R W Moulton, "Critical flow of vapour liquid mixtures", 1967 AIChEJ 13 52-60

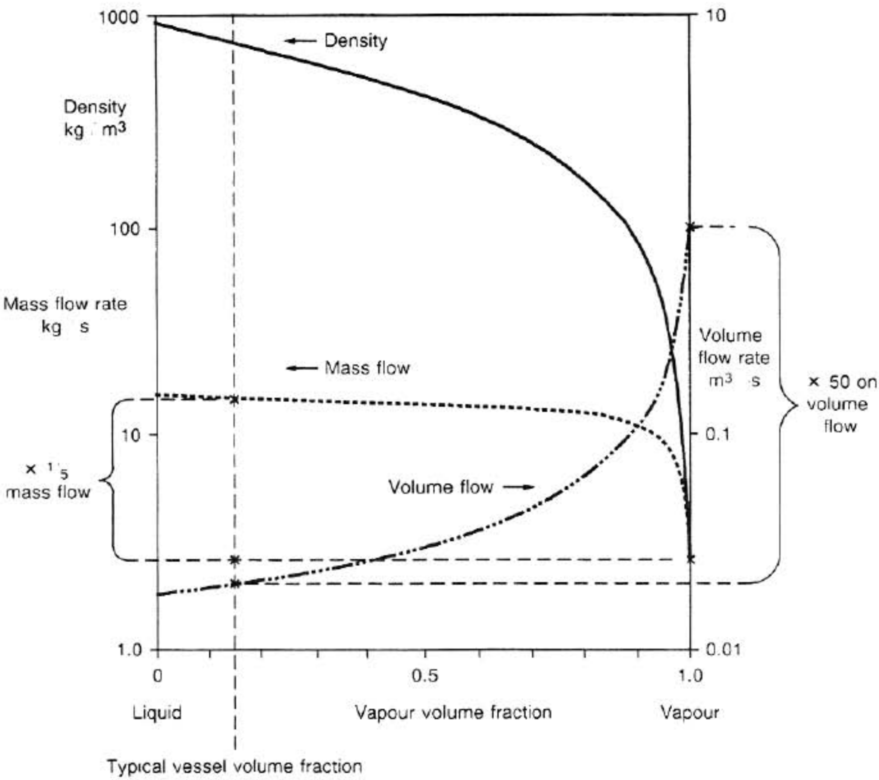
10. F J Moody "Maximum flowrate of a single component two phase mixture", 1969(2) J Heat Tr 135

11. S Levy, "Prediction of two phase critical flow rate", 1965(2) J Heat Tr 53

12. "Emergency relief systems effluent control", Centre for Chemical Process Safety, AIChE, 1994

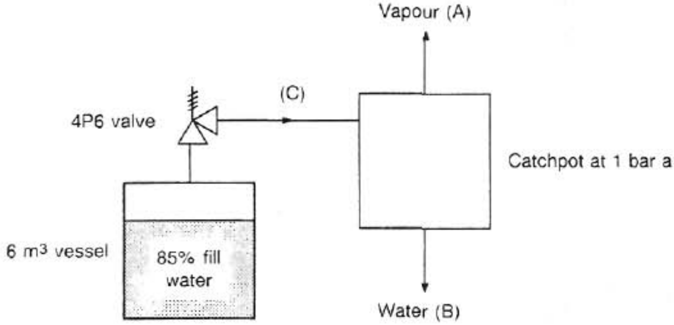
13. S D Morris, "Single component 2 phase choked flow", Note TP10, 1988 Heat Transfer and Fluid Flow Service, Harwell.

FIGURE 1 EFFECT OF VAPOUR VOLUME FRACTION ON CHOKED FLOWRATE



Conditions : Saturated water at 5 bar a, 152°C
Choked flow through 41 cm^2 orifice
Homogenous equilibrium flow

FIGURE 2 EFFECT OF RELIEF VOID FRACTION ON FLOWRATES TO AND FROM CATCHPOT



Conditions : Saturated water at 5 bar a, 152°C
Choked flow through 41 cm² orifice

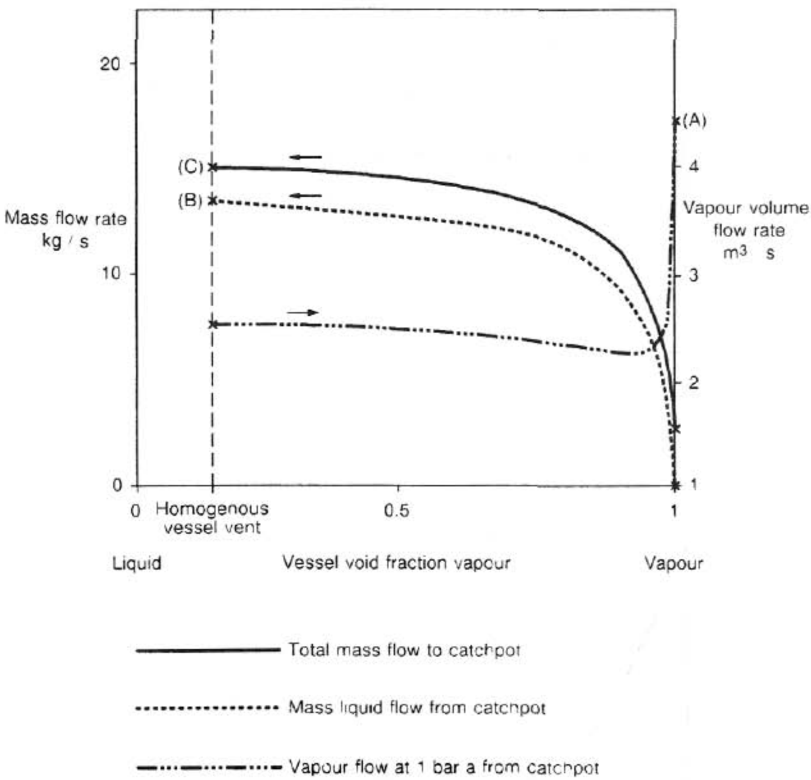


FIGURE 3 EXPERIMENTAL CRITICAL MASS FLUX RATIO vs QUALITY FOR AIR-WATER FLOW (data Fauske 1965 Pc = 1.17 bar) (13)

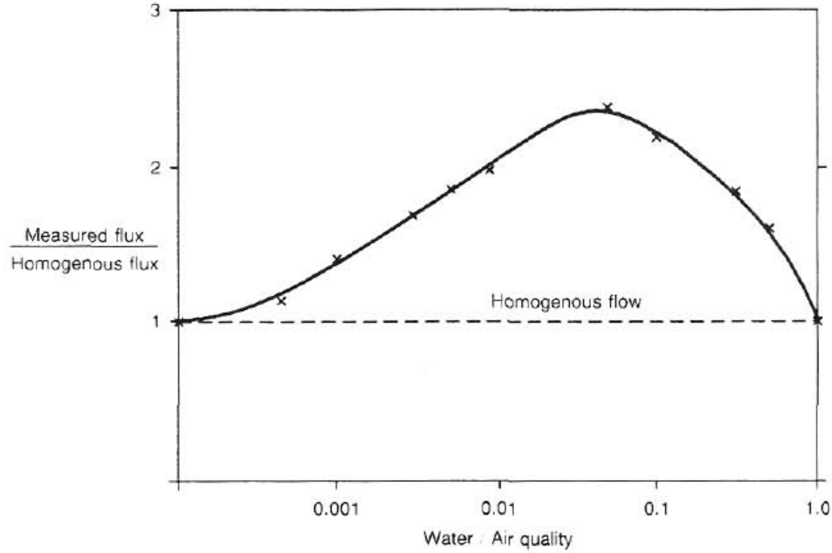


FIGURE 4 EXPERIMENTAL CRITICAL MASS FLUX RATIO vs EXIT QUALITY FOR CHOKED STEAM / WATER FLOW
(data Henry 1968 Pc = 2.76 & 4.14 bar; Faletti & Moulton 1963 Pc = 2.76 bar) (13)